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(54) **SIC POWER SEMICONDUCTOR DEVICE WITH INTEGRATED BODY DIODE**

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(51) **Int. Cl.**

(57) **ABSTRACT**

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**H01L 29/16** (2006.01)  
**H01L 29/872** (2006.01)  
**H01L 29/78** (2006.01)

Embodiments of SiC devices and corresponding methods of manufacture are provided. In some embodiments, the SiC device has shielding regions at the bottom of some gate trenches and non-linear junctions formed with the SiC material at the bottom of other gate trenches. In other embodiments, the SiC device has the shielding regions at the bottom of the gate trenches and arranged in rows which run in a direction transverse to a lengthwise extension of the trenches. In still other embodiments, the SiC device has the shielding regions and the non-linear junctions, and wherein the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of the trenches.

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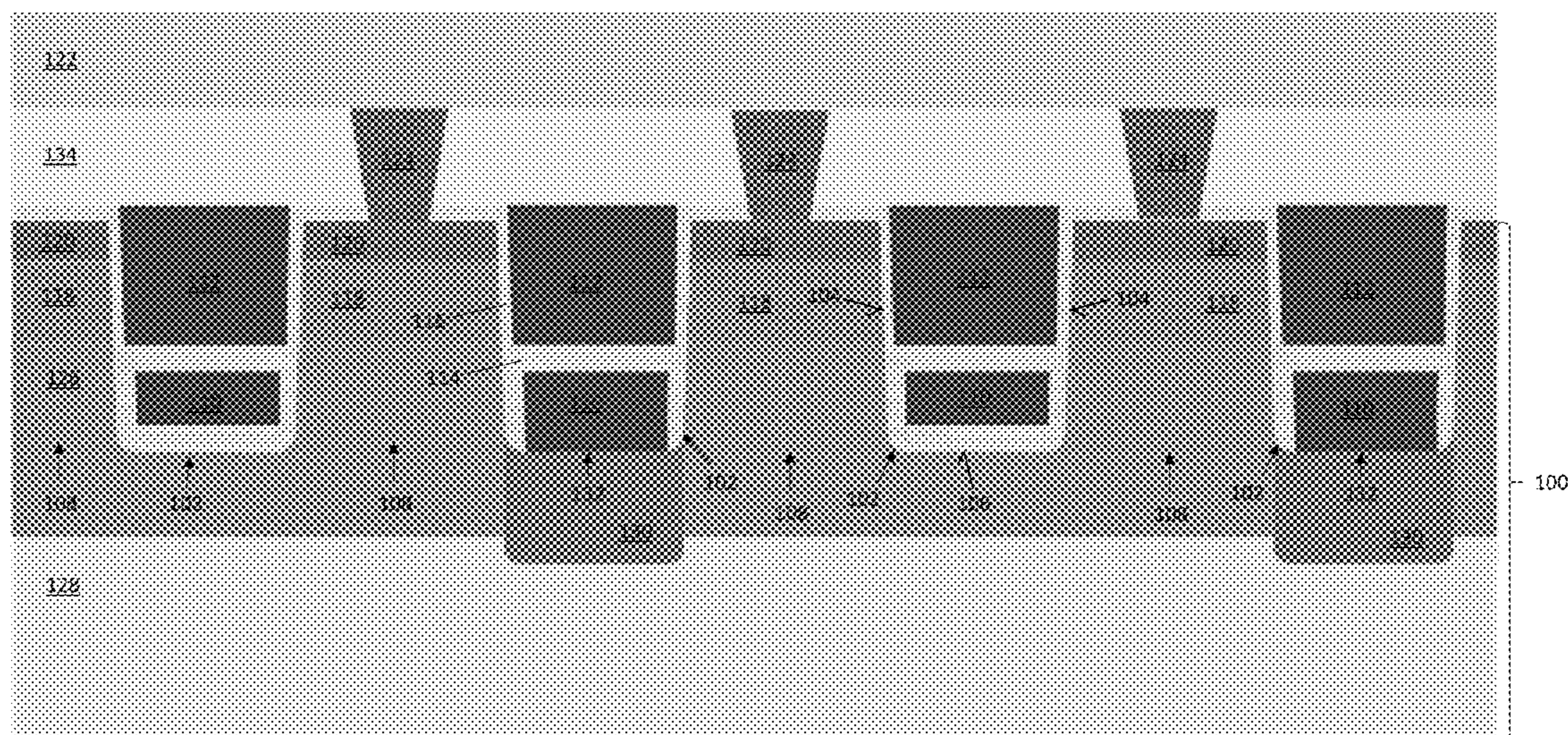
CPC ..... **H01L 29/407** (2013.01); **H01L 29/1608** (2013.01); **H01L 29/4236** (2013.01); **H01L 29/7827** (2013.01); **H01L 29/872** (2013.01)

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See application file for complete search history.

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A-A'





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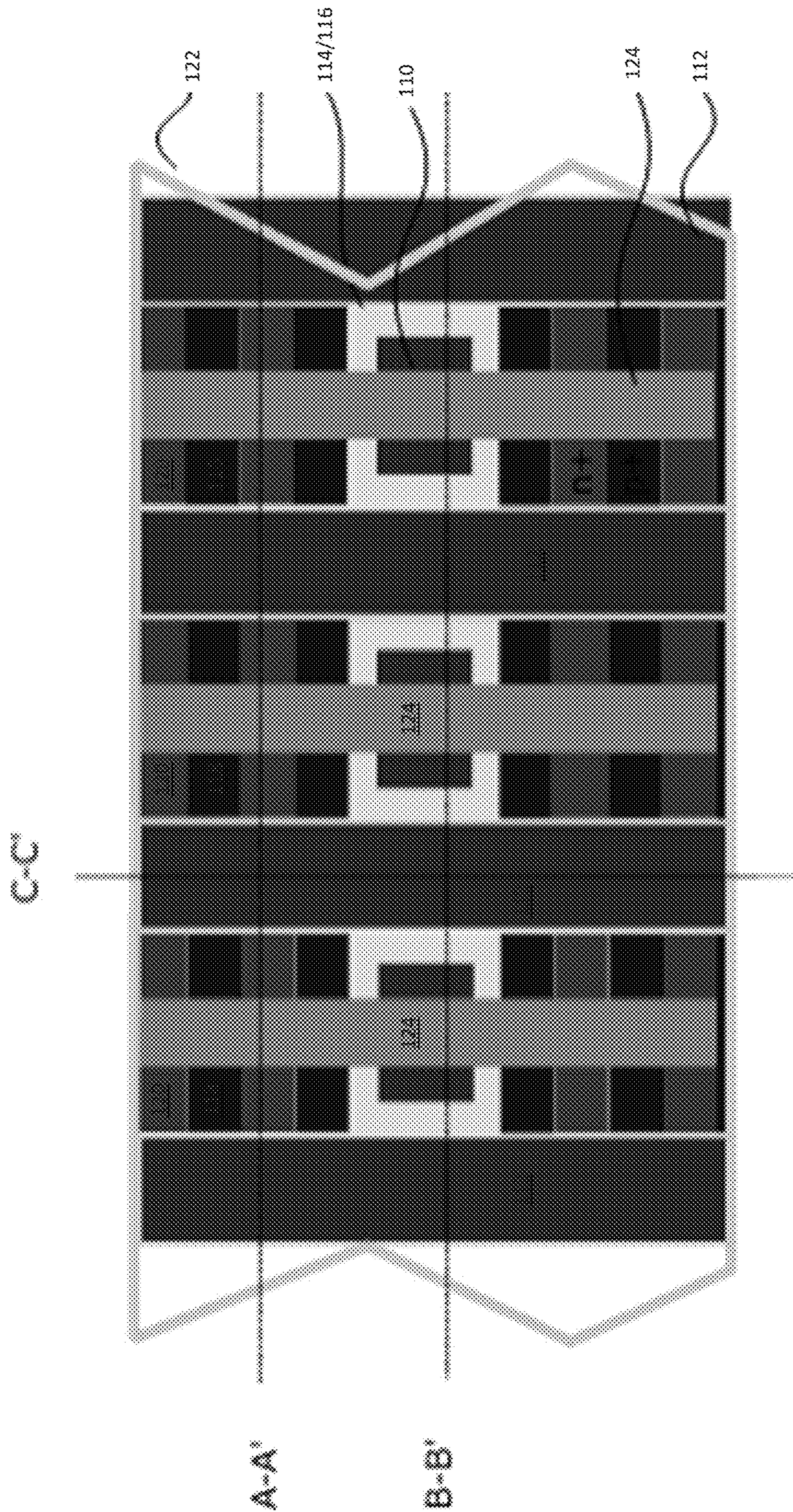


Figure 1



A-A'

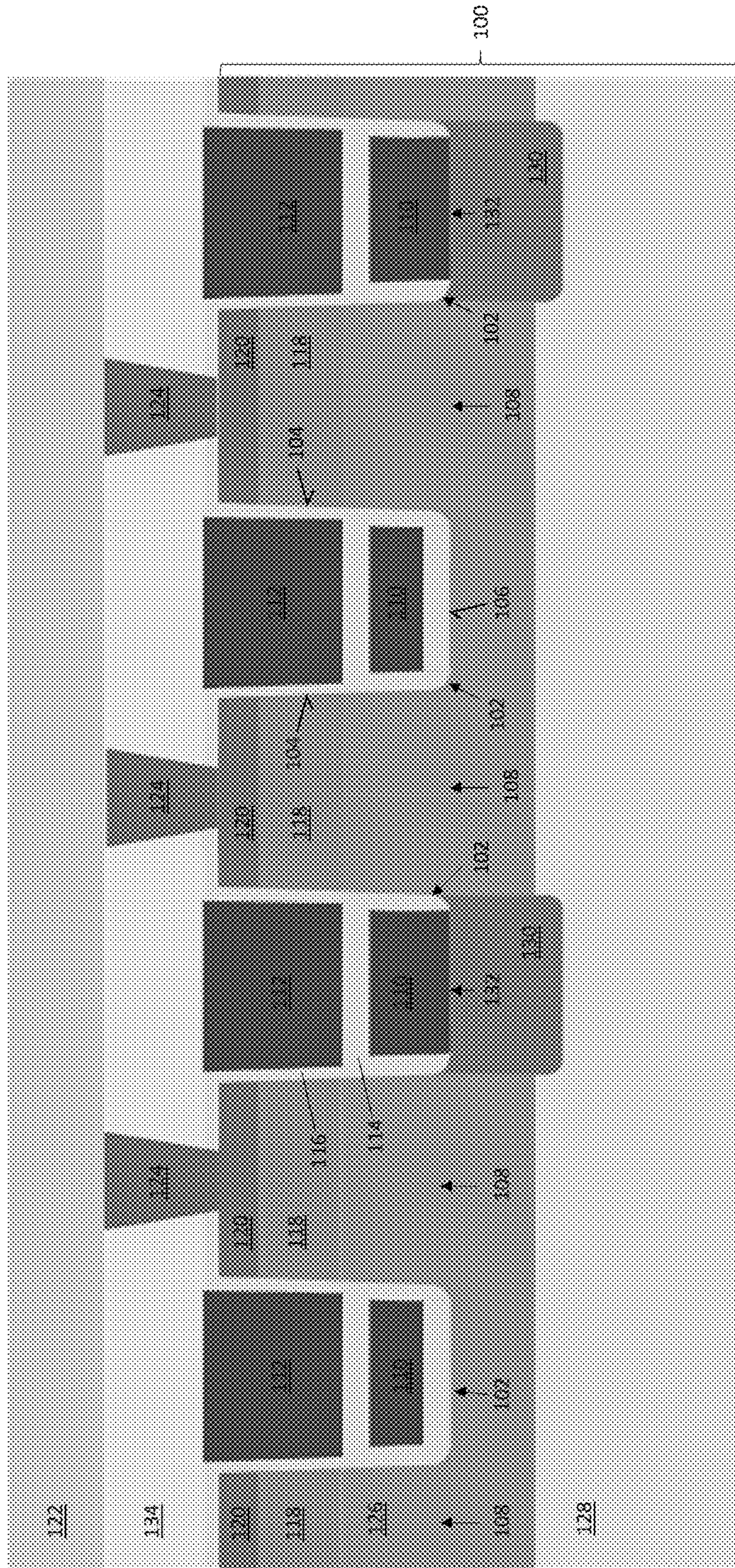


Figure 2



B-B'

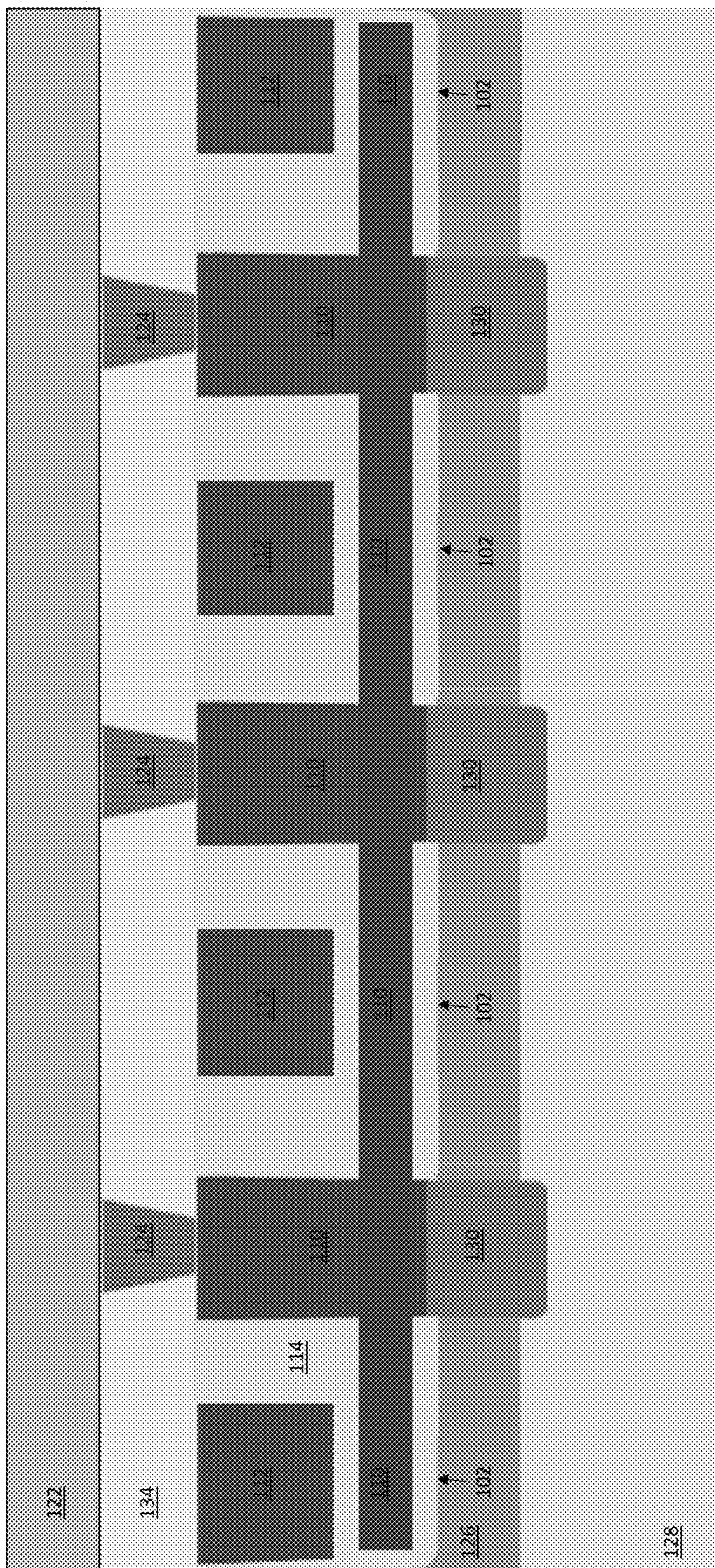


Figure 3



C-C

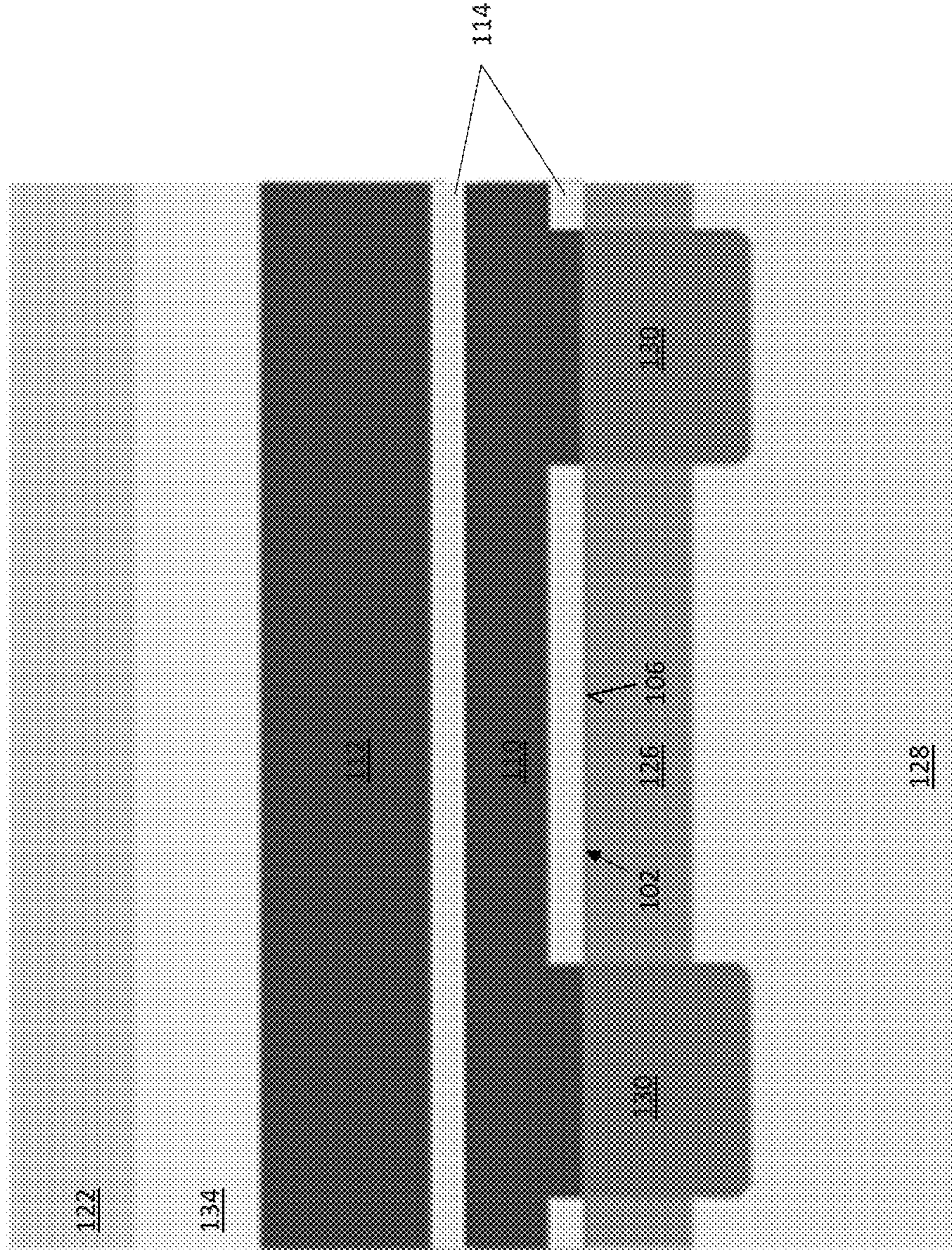


Figure 4



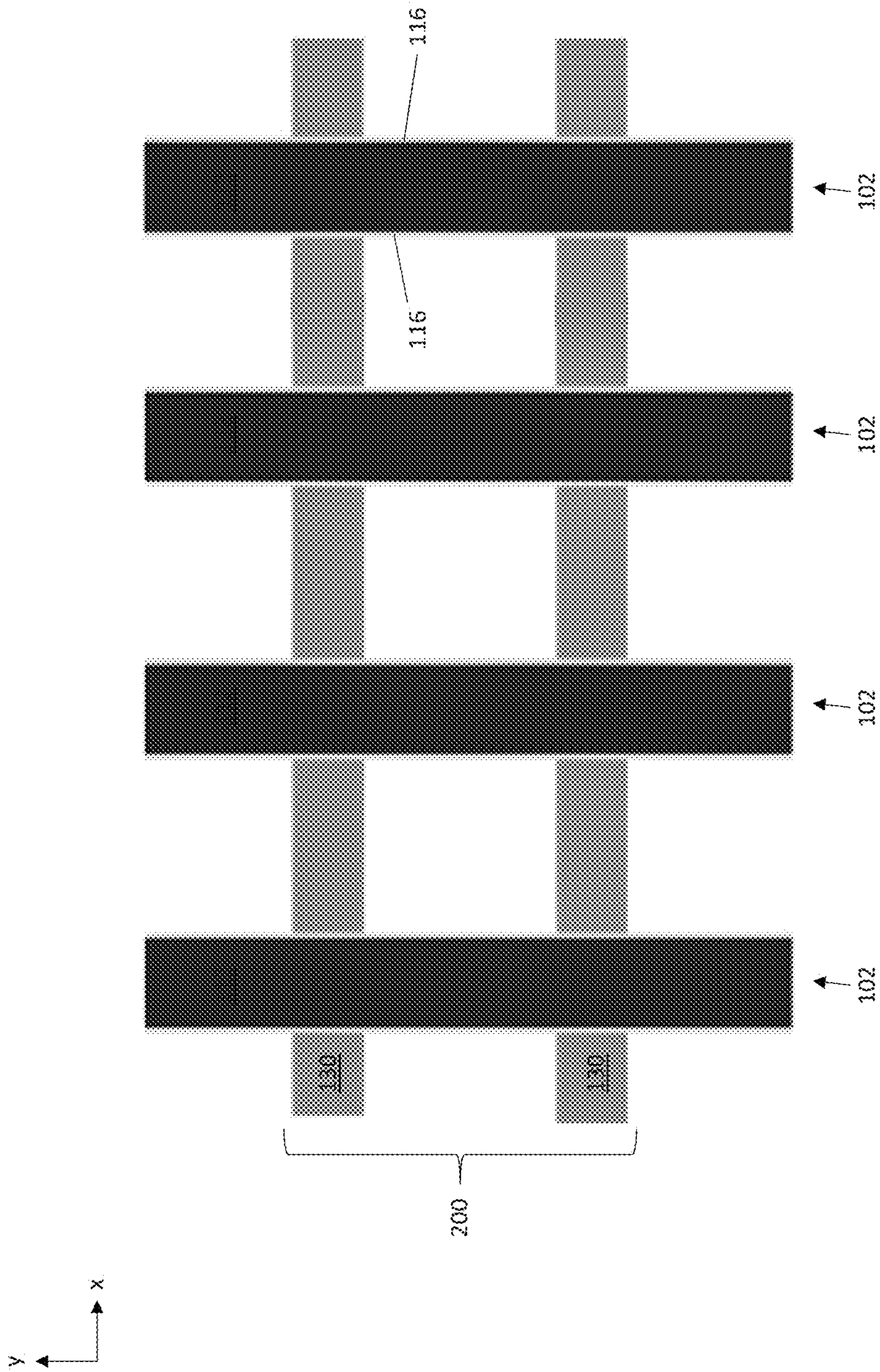


Figure 5

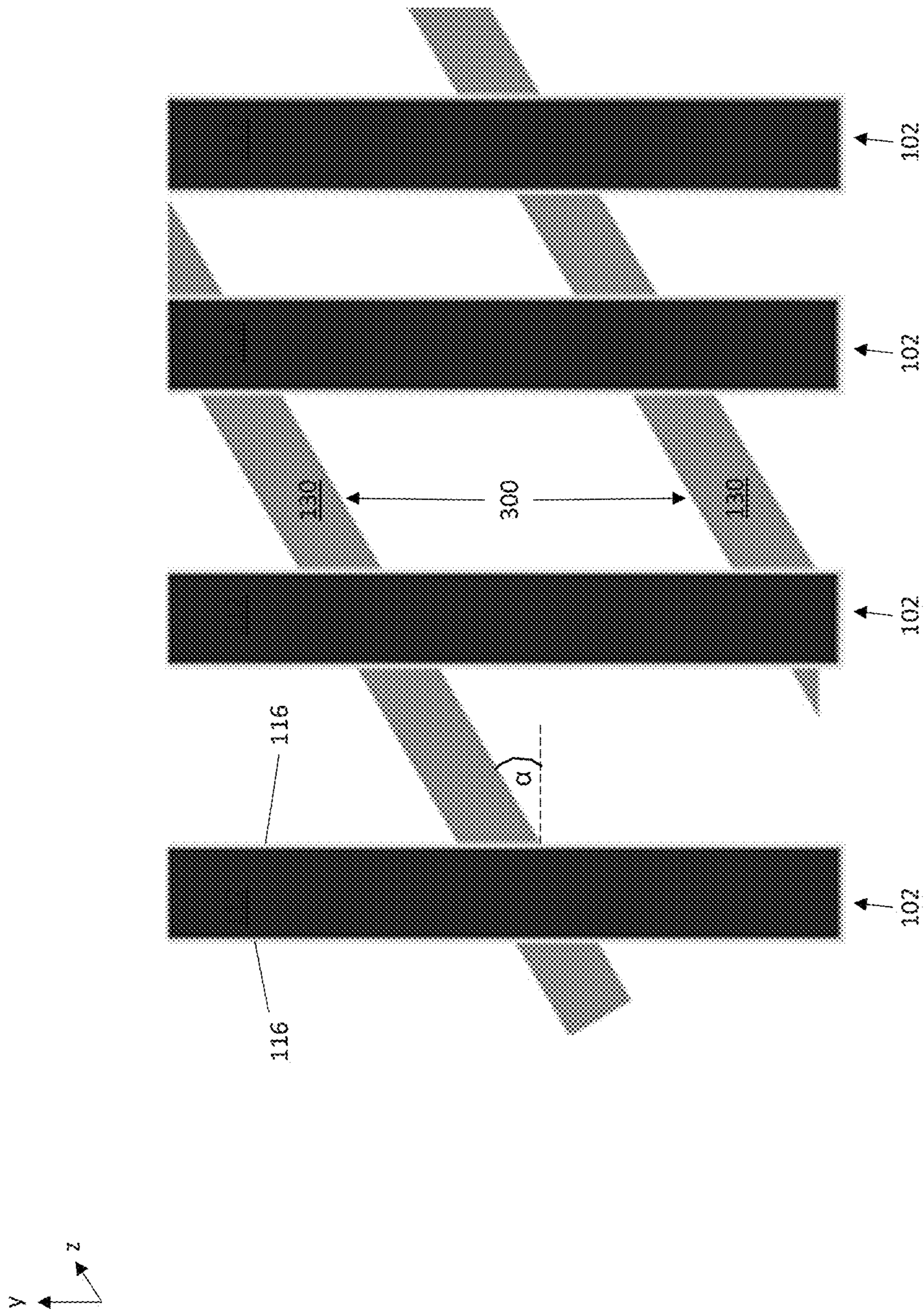


Figure 6



A-A'

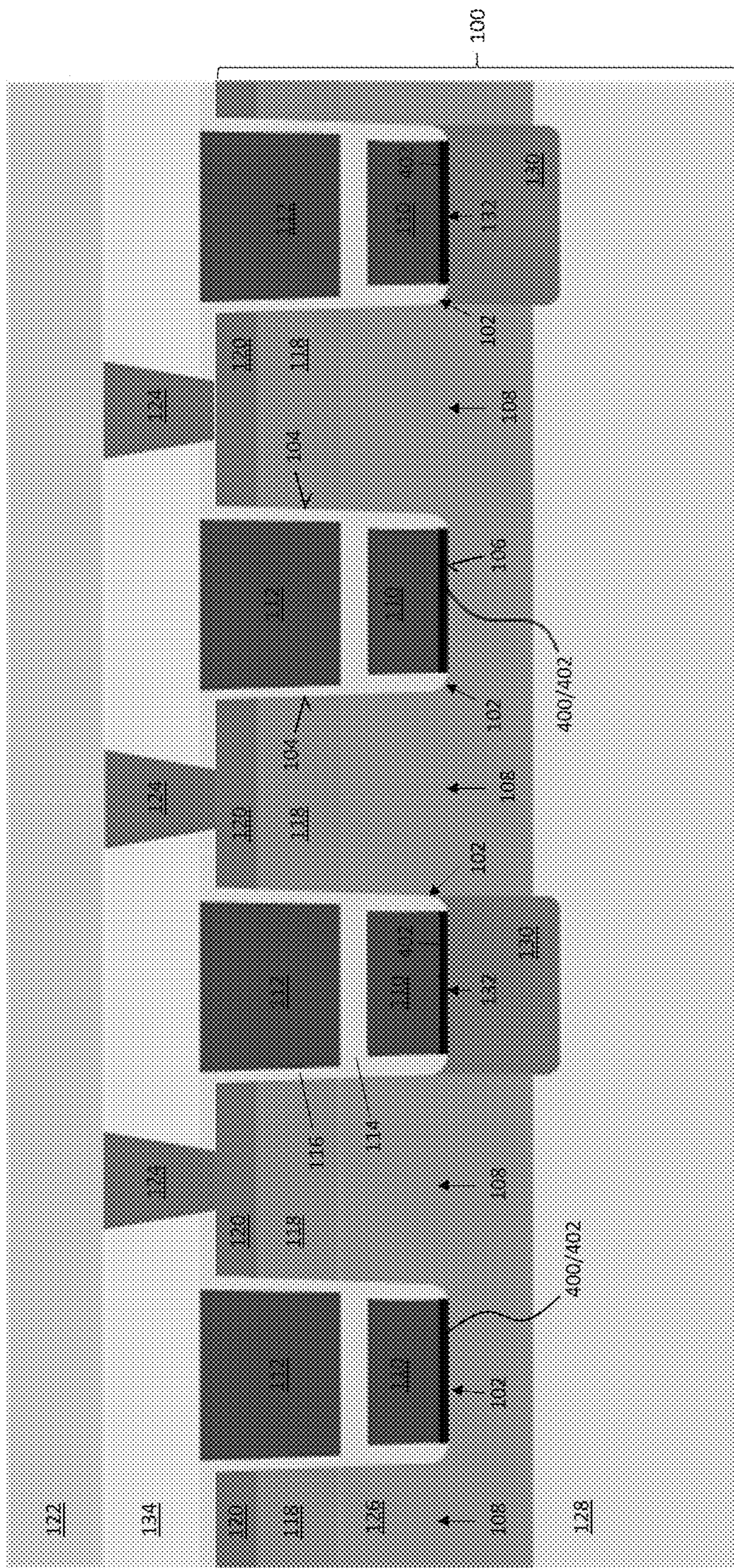


Figure 7



A-A'

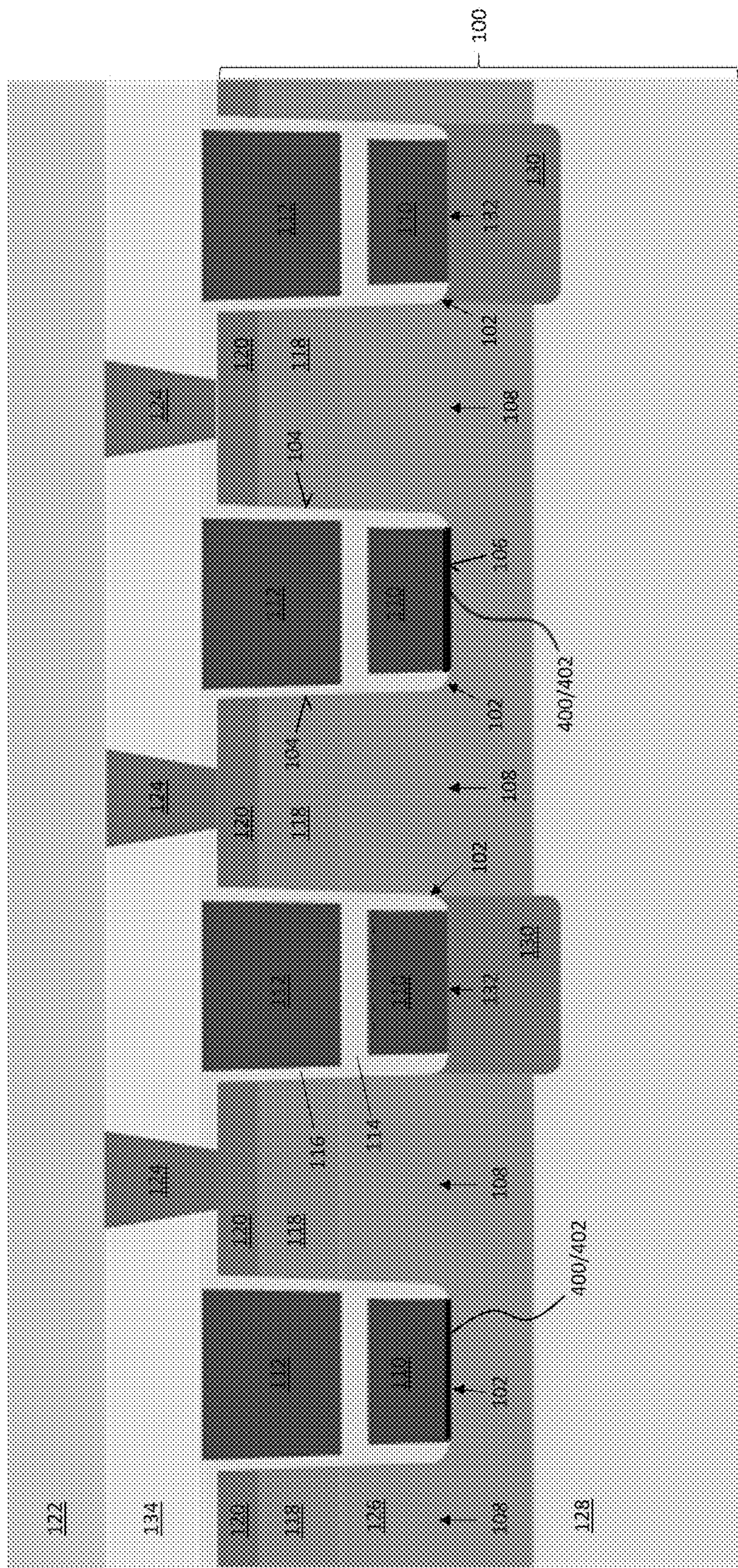


Figure 8



A-A'

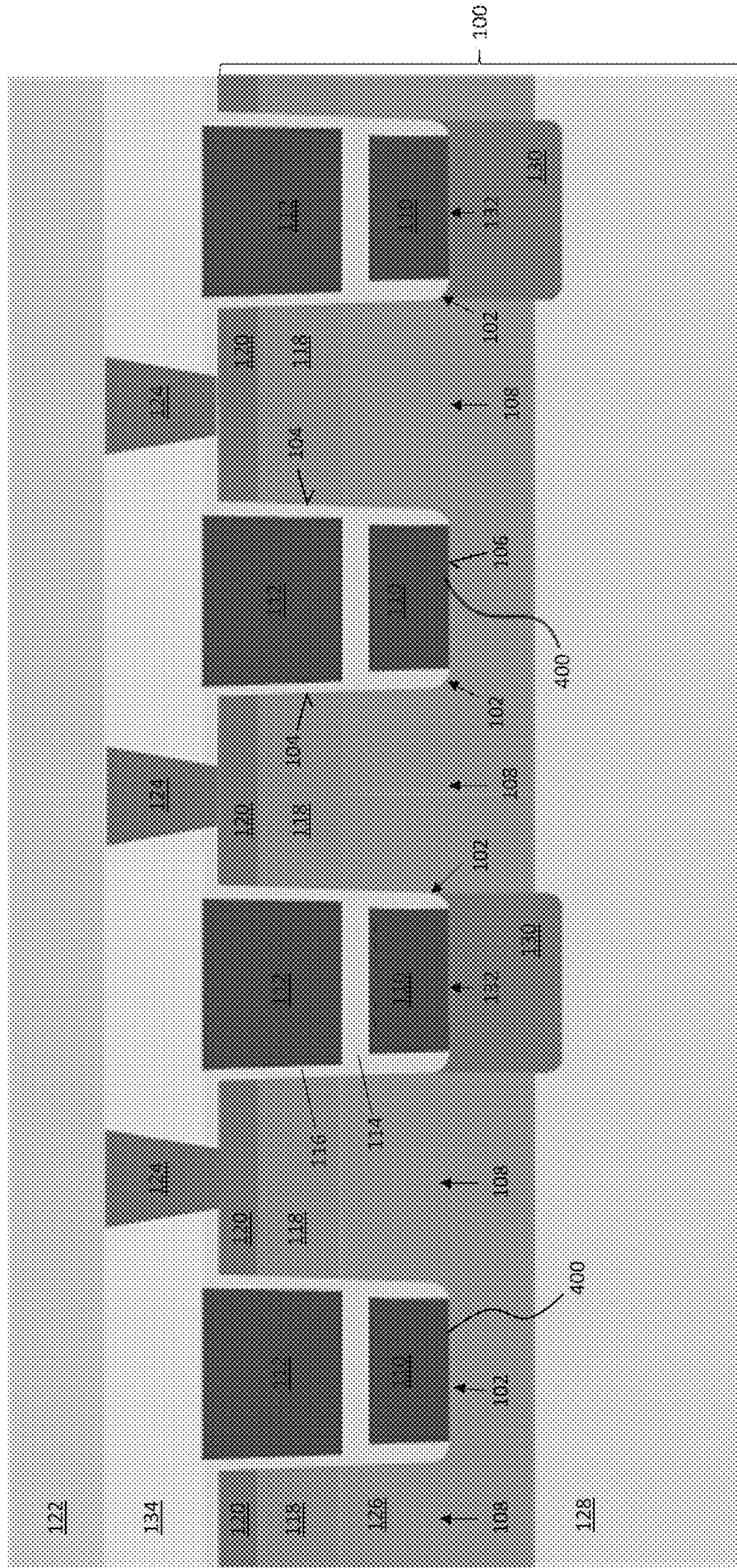
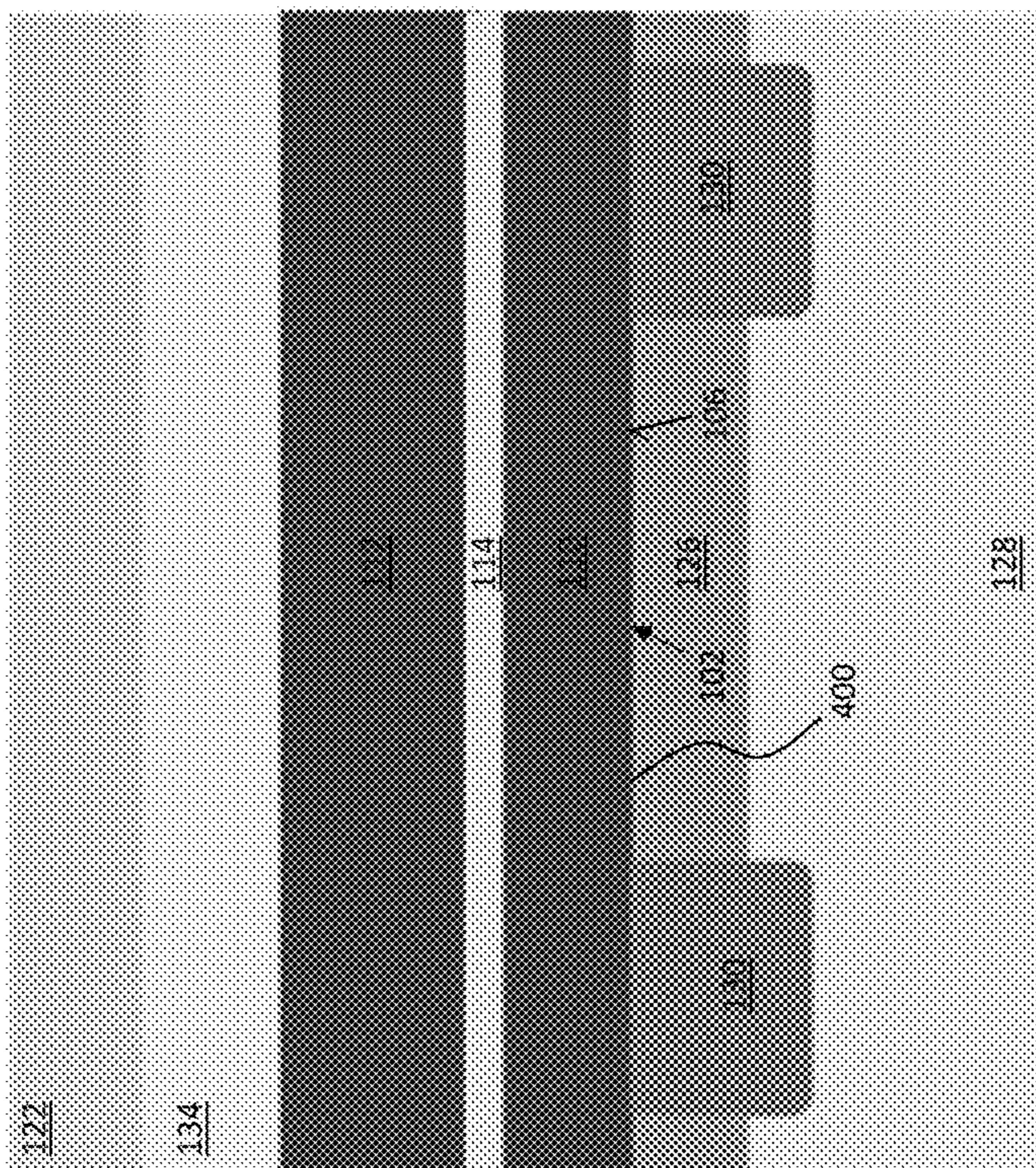


Figure 9



C-C'



C-C'

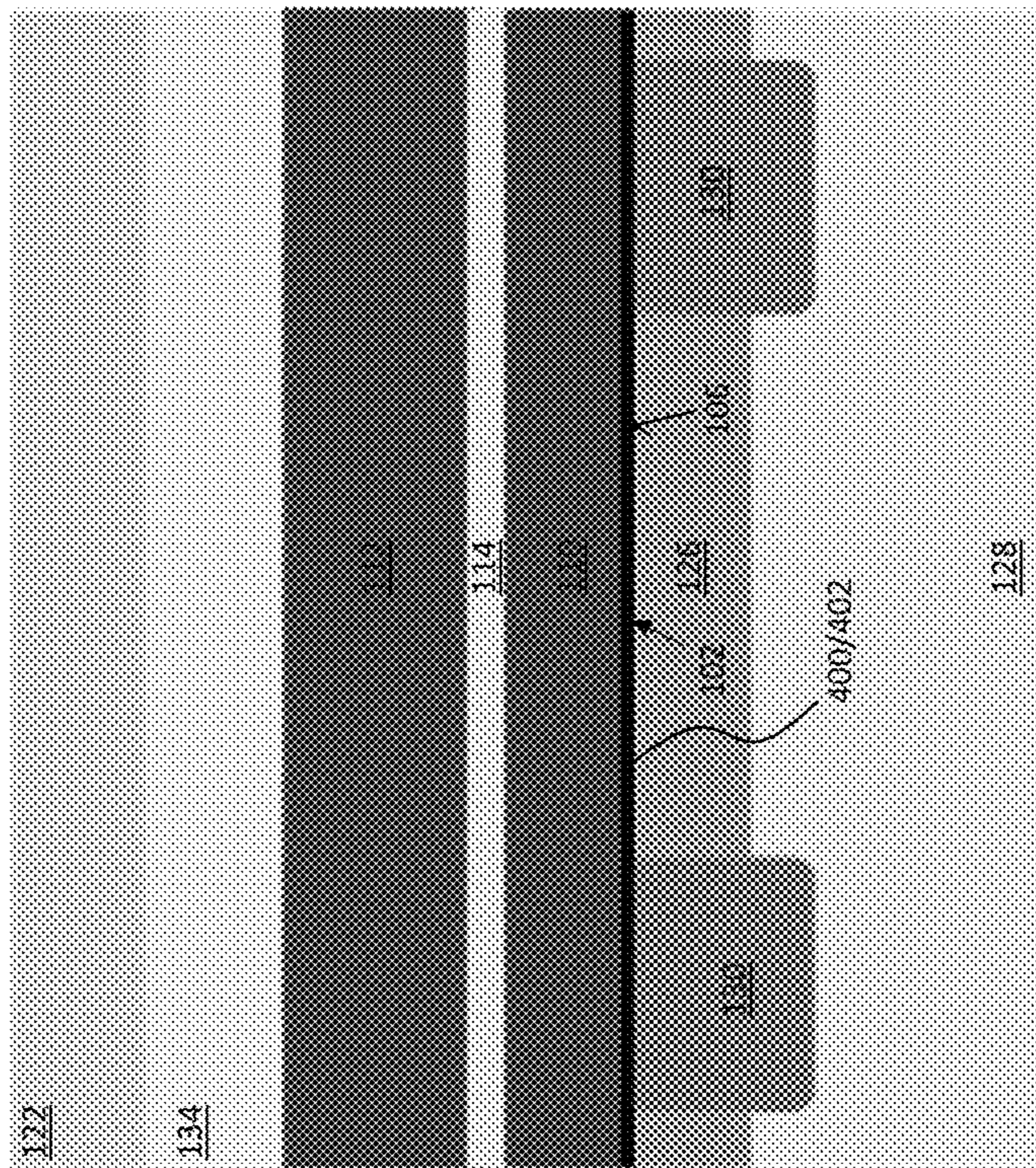


Figure 11

Figure 10



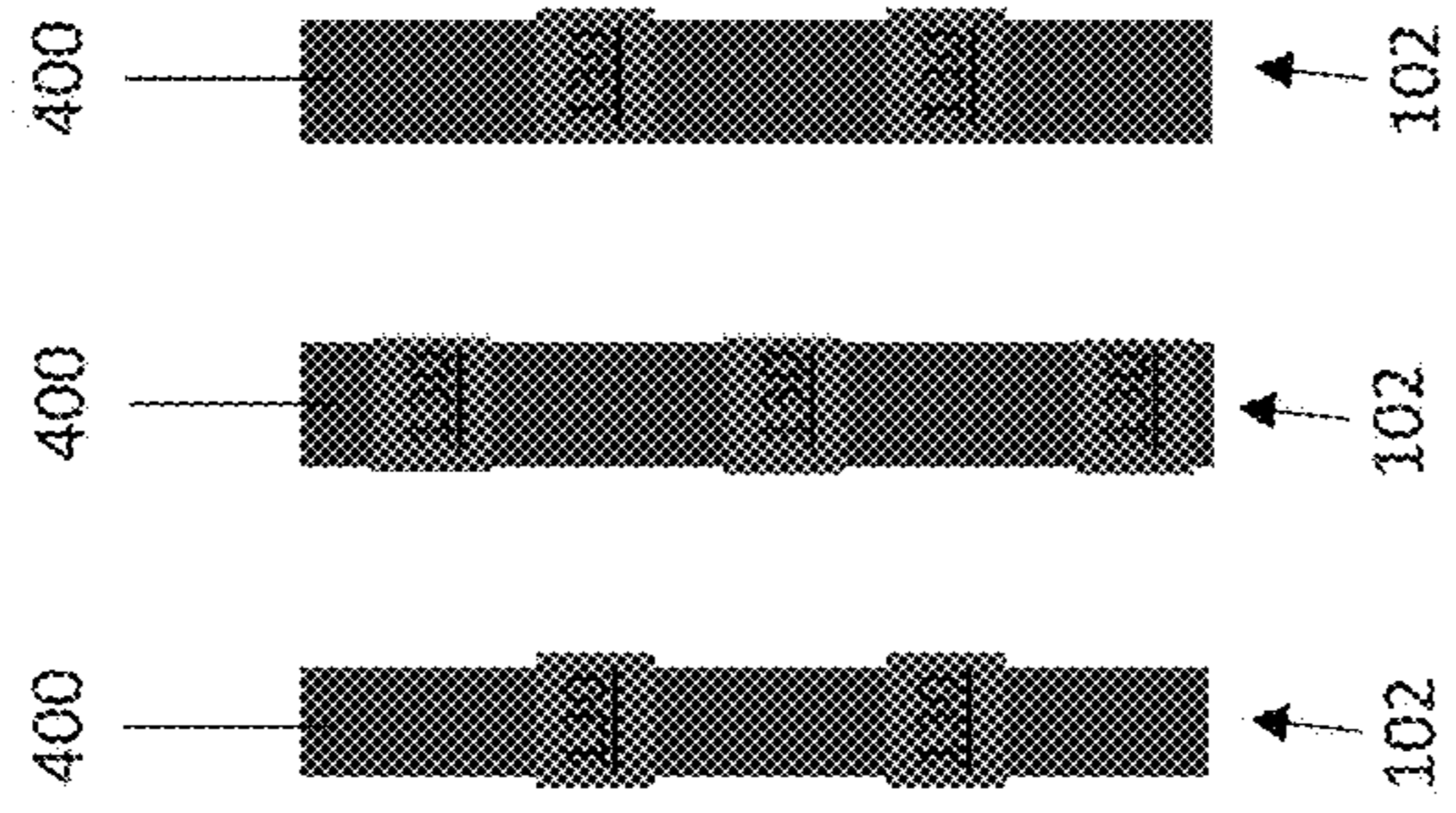


Figure 12

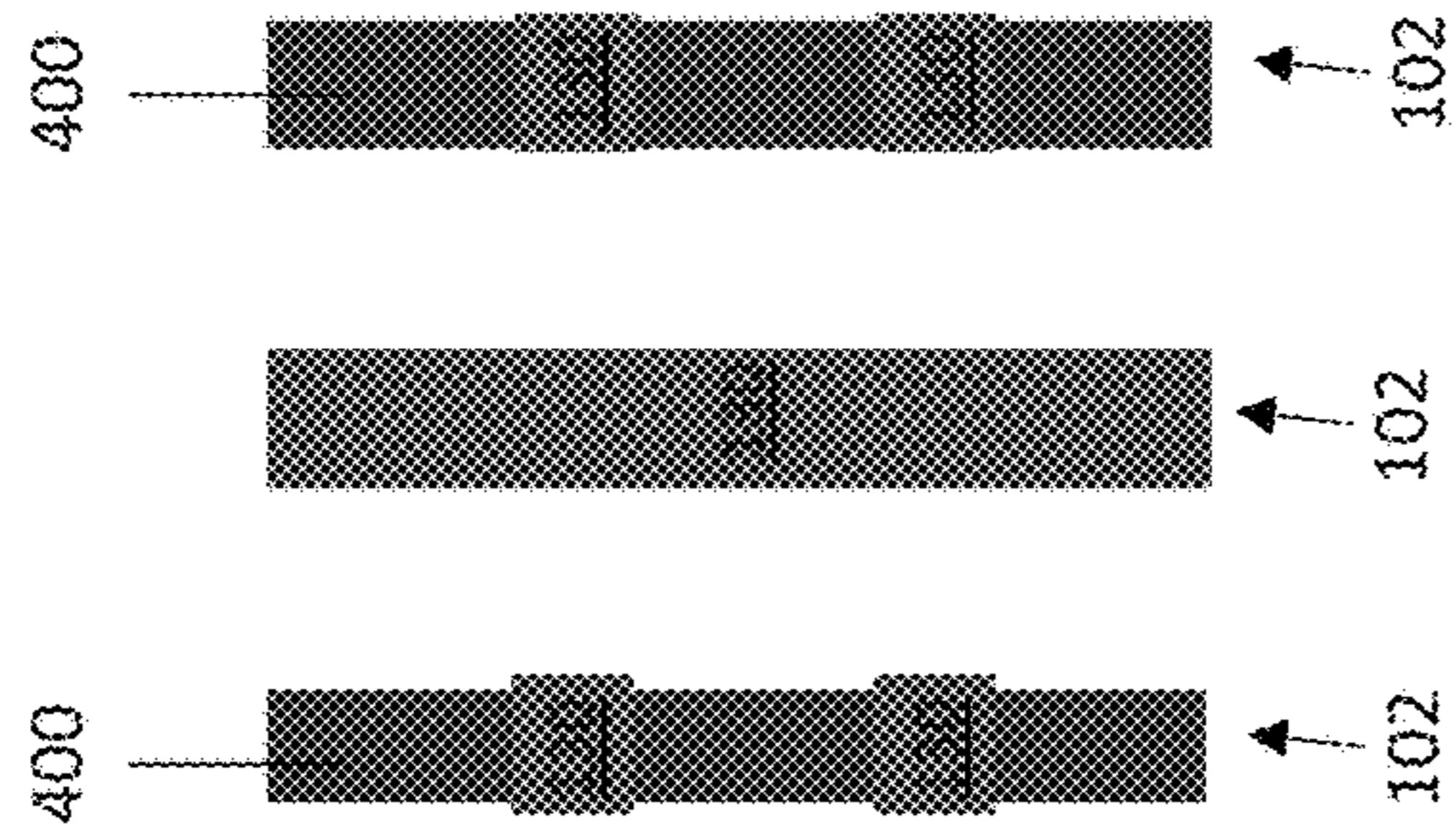


Figure 13

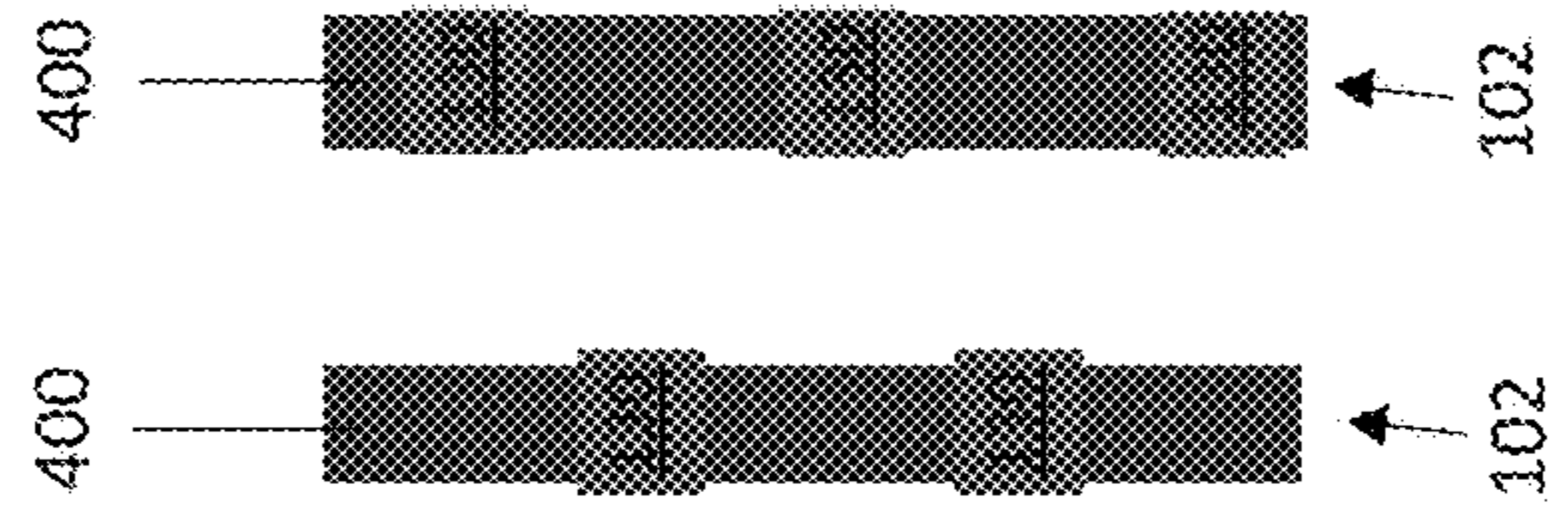


Figure 14



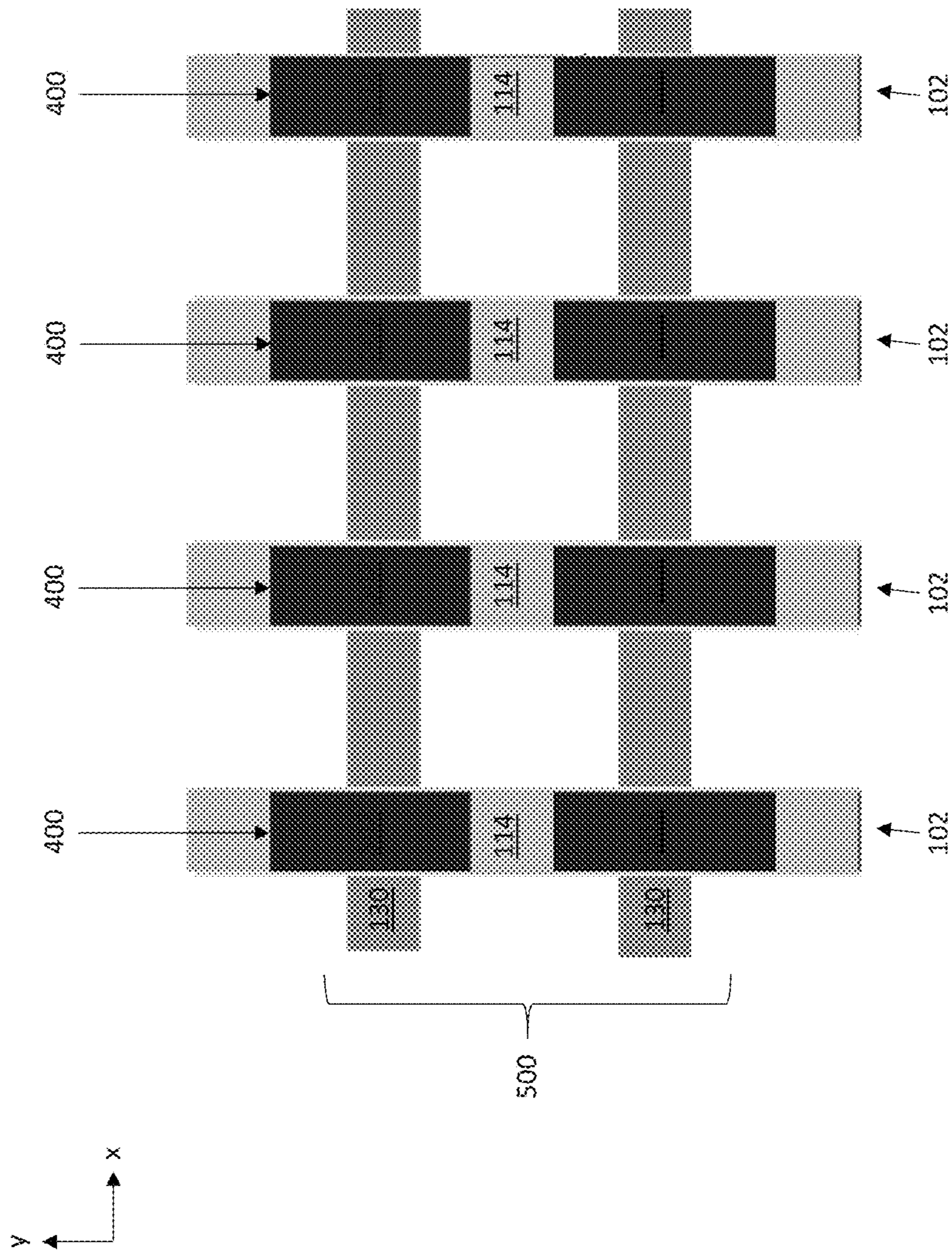


Figure 15



1

## SIC POWER SEMICONDUCTOR DEVICE WITH INTEGRATED BODY DIODE

### BACKGROUND

Power MOSFET devices usually have an integrated body diode. This includes Si and SiC-based power MOSFET devices. The forward voltage drop of a bipolar SiC diode (about 2.7V to 4V) is considerably higher than the forward voltage drop of a bipolar Si diode (about 0.7V to 1V), which translates to increased diode conduction losses. While the channel of a power MOSFET in reverse conduction mode is usually turned on to reduce the conduction losses, a dead-time is needed in the transition phases where the channel cannot conduct. The dead-time is usually minimized as much as possible, but the length of the dead-time is also related to the application field. For example, the dead-time can be as low as 50 to 100 ns in synchronous rectification stages of low-voltage DC/DC converters, but may reach 1 to 2  $\mu$ s for high-voltage motor-drive applications. Applications that run at larger switching frequencies generate a higher amount of diode conduction losses. Overall, losses related to the body diode may vary significantly. Particularly for low-voltage power MOSFET devices used at relatively high switching frequencies, the losses may be so large that a Schottky diode or MGD (MOS-gated diode) may be provided to lower the losses due to the lower forward voltage of such devices.

Additionally, the body diode of a SiC MOSFET device can be viewed as a bipolar device the operation of which can cause bipolar degradation effects. The degradation is triggered by recombination energy which is transferred to the crystal and may cause a reconfiguration of the crystal or result in growth of remaining basal plane dislocations. The reconfigured areas may become more resistive, altering the properties of the device. Integration of a unipolar diode such as a Schottky diode can prevent such a degradation mechanism as long as the unipolar diode can conduct the nominal current through the device.

Thus, there is a need for a SiC-based power semiconductor device having an integrated body diode but with reduced conduction losses and reduced bipolar degradation.

### SUMMARY

According to an embodiment of a semiconductor device, the semiconductor device comprises: a SiC material of a first conductivity type; a plurality of trenches extending into the SiC material, each trench having opposing sidewalls and a bottom; a first electrode formed in a lower part of the trenches; a second electrode formed in an upper part of the trenches and insulated from the first electrode and the SiC material; a channel region of a second conductivity type adjacent the opposing sidewalls of each trench; a source region of the first conductivity type above the channel region and adjacent the opposing sidewalls of each trench; a shielding region of the second conductivity type at the bottom of a first subset of the trenches, each shielding region being electrically connected to the corresponding first electrode through an opening in an insulating material at the bottom of the first subset of trenches; and a non-linear junction formed with the SiC material at the bottom of a second subset of the trenches different than the first subset.

Each of trenches may be stripe-shaped and may extend along a lengthwise extension, which corresponds to the main extension direction of the trench. In this case, the trenches may have the shape of an elongated rectangle in a top view.

2

Lengthwise extensions of neighboring trenches may run in parallel. It may, however, also be possible that the trenches have a quadratic, a hexagonal or a circular shape in a top view.

5 The non-linear junction may be formed between the SiC material and the first electrode at the bottom of the second subset of trenches. The non-linear junction may be a diode, such as, for instance, a pn diode or a Schottky diode.

10 Separately or in combination, the first electrode formed in the lower part of the trenches may comprise a highly conducting material (e.g. with an electrical conductivity of above  $10^{-4}$  S/cm). For example, the first electrode formed in the lower part of the trenches may comprise a semiconductor material or a metal. In some embodiments, the semiconductor material may be doped polysilicon.

15 Separately or in combination, a metal may be formed below the first electrode in the second subset of trenches, the non-linear junction is a Schottky junction, and the Schottky junction is formed between the SiC material and the metal at the bottom of the second subset of trenches. Here and in the following, a metal may be an elementary metal or a metal alloy.

20 Separately or in combination, the first electrode may contact the shielding region at the bottom of the first subset of trenches, e.g. via an ohmic contact.

25 Separately or in combination, a metal may be formed below the first electrode in the first subset of trenches and the metal may contact the shielding region at the bottom of the first subset of trenches.

30 Separately or in combination, the shielding regions and the non-linear junctions may be arranged in an alternating manner below the plurality of trenches. In some embodiments, the shielding regions are arranged only at the bottom of the first subset of trenches and the non-linear junctions are arranged only at the bottom of the second subset of trenches. In this case, the shielding regions and the non-linear junctions may alternate along a direction transverse (e.g. with an angle of at least  $40^\circ$  and at most  $140^\circ$ ) to the sidewalls of the trenches (e.g., transverse to the lengthwise extension in case of stripe-shaped trenches). In other embodiments, at least one of the shielding regions and the non-linear junctions may be arranged at the bottom of the first subset of trenches and at the bottom of the second subset of trenches. In this case, the shielding regions and the non-linear junctions may alternate at least along a direction parallel to the bottom of the trenches (e.g., along the lengthwise extension in case of stripe-shaped trenches). In addition, the shielding regions and the non-linear junctions may also alternate along one of the trenches, in particular along the lengthwise extension.

35 Separately or in combination, the shielding regions may be arranged at corners of a grid and/or the shielding regions may form part of a grid. For example, the shielding regions and the trenches may be arranged in a grid or the shielding regions alone may be arranged in a grid. It is possible for the shielding regions to have a different pitch than the trenches. The pitch of the trenches (shielding regions) may be a center-to-center distance of neighboring trenches (neighboring shielding regions). The meshes of the grid may be rectangular or may have the shape of a rhombus.

40 Separately or in combination, the shielding regions may extend in parallel with one another in lines that run parallel to the trenches. In some embodiments, the shielding region may extend along an entire trench. Each shielding region may be assigned to one of the trenches of the first subset of trenches in a one-to-one manner.

45 Separately or in combination, the insulating material may be present at the bottom of the trenches (e.g. at the bottom



the trenches of the first subset of trenches) between adjacent ones of the shielding regions.

Separately or in combination, some of the shielding regions may be segmented and other ones of the shielding regions may be contiguous over a length of the trenches. The shielding regions may be arranged at the bottom of the first subset of trenches and at the bottom of the second subset of trenches. For example, the segmented shielding regions may be arranged at the bottom of the second subset of trenches and the contiguous shielding regions may be arranged at the bottom of the first subset of trenches. "Contiguous" in this context may mean that the shielding region extends along at least 90% of the trench in a lengthwise extension of the trench. "Segmented" may mean that a plurality of shielding regions are arranged at the bottom of each trench, wherein shielding regions of one trench are not interconnected by parts of the shielding regions. In the latter case, shielding regions of neighboring trenches may be interconnected.

Separately or in combination, the shielding regions may be arranged in rows which run in a direction transverse (e.g., with an angle of at least 40° and at most 140°) to a lengthwise extension of the trenches.

According to another embodiment of a semiconductor device, the semiconductor device comprises: a SiC material of a first conductivity type; a plurality of trenches extending into the SiC material, each trench having opposing sidewalls and a bottom; a first electrode formed in a lower part of the trenches; a second electrode formed in an upper part of the trenches and insulated from the first electrode and the SiC material; a channel region of a second conductivity type adjacent the opposing sidewalls of each trench; a source region of the first conductivity type above the channel region and adjacent the opposing sidewalls of each trench; and a shielding region of the second conductivity type at the bottom of the trenches and electrically connected to the corresponding first electrode through an opening in an insulating material at the bottom of the trenches, wherein the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of the trenches.

The insulating material may be present at the bottom of the trenches between adjacent rows of the shielding regions.

Separately or in combination, the semiconductor device may further comprise a non-linear junction formed with the SiC material at the bottom of the trenches.

Separately or in combination, a metal may be formed below the first electrode in the trenches, the non-linear junction is a Schottky junction, and the Schottky junction is formed between the SiC material and the metal at the bottom of the trenches.

Separately or in combination, the insulating material may be present at the bottom of the trenches between adjacent rows of the shielding regions to divide the non-linear junction in the same trench into a plurality of non-linear junction segments separated from one another by the insulating material.

Separately or in combination, the shielding regions may be contiguous over a length of the trenches.

Separately or in combination, the rows of shielding regions may run in a direction orthogonal or nearly orthogonal to the lengthwise extension of the trenches.

Those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

#### BRIEF DESCRIPTION OF THE FIGURES

The elements of the drawings are not necessarily to scale relative to each other. Like reference numerals designate

corresponding similar parts. The features of the various illustrated embodiments can be combined unless they exclude each other. Embodiments are depicted in the drawings and are detailed in the description which follows.

FIG. 1 illustrates a partial top plan view of an embodiment of a semiconductor device having shielding regions formed in a SiC material.

FIG. 2 illustrates a cross-sectional view of the semiconductor device along the line labelled A-A' in FIG. 1.

FIG. 3 illustrates a cross-sectional view of the semiconductor device along the line labelled B-B' in FIG. 1.

FIG. 4 illustrates a cross-sectional view of the semiconductor device along the line labelled C-C' in FIG. 1.

FIG. 5 illustrates an embodiment of a layout in which the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of gate trenches included in the device.

FIG. 6 illustrates another embodiment of a layout in which the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of gate trenches included in the device.

FIGS. 7 through 11 illustrate respective partial cross-sectional views of embodiments of a semiconductor device having shielding regions and non-linear junctions formed in a SiC material.

FIGS. 12 through 14 illustrate respective partial top-down plan views of different embodiments of a shielding region layout in conjunction with a non-linear junction layout for a SiC-based semiconductor device.

FIG. 15 illustrates a partial top-down plan view of another embodiment of a shielding region layout in conjunction with a non-linear junction layout for a SiC-based semiconductor device.

#### DETAILED DESCRIPTION

The embodiments described herein may provide a SiC-based power semiconductor device with reduced conduction losses and reduced bipolar degradation. In some embodiments, the SiC device has shielding regions at the bottom of some gate trenches and non-linear junctions formed with the SiC material at the bottom of other gate trenches. In other embodiments, the SiC device has the shielding regions at the bottom of the gate trenches and arranged in rows which run in a direction transverse to a lengthwise extension of the gate trenches. In still other embodiments, the SiC device has the shielding regions and the non-linear junctions, and the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of the gate trenches.

FIG. 1 illustrates a partial top plan view of an embodiment of a semiconductor device. FIG. 2 illustrates a cross-sectional view of the semiconductor device along the line labelled A-A' in FIG. 1. FIG. 3 illustrates a cross-sectional view of the semiconductor device along the line labelled B-B' in FIG. 1. FIG. 4 illustrates a cross-sectional view of the semiconductor device along the line labelled C-C' in FIG. 1. The semiconductor device may be a power semiconductor device such as a power MOSFET.

The semiconductor device includes a SiC material **100** of a first conductivity type. The SiC material **100** may include one or more SiC epitaxial layers grown on a substrate (not shown and/or removed after epitaxial growth). In the case of an n-channel power MOSFET, the SiC material **100** has n-type background doping. In the case of a p-channel power MOSFET, the SiC material **100** has p-type background doping.



Gate trenches **102** extend into the SiC material **100**, each gate trench **102** having opposing sidewalls **104** and a bottom **106**. Mesas **108** of the SiC material **100** are present between adjacent ones of the gate trenches **102**. A buried electrode **110** is formed in a lower part of the gate trenches **102**. The buried electrodes **110** may be electrically connected to source potential, e.g., in the case of a power MOSFET device. A gate electrode **112** is formed in an upper part of the gate trenches **102**. The buried electrodes **110** and the gate electrodes **112** are electrically conductive and may be formed from doped polysilicon such as p+ polysilicon, from metal, etc. Each gate electrode **112** is insulated from the underlying buried electrode **110** by an insulating material **114** such as a field oxide. The gate electrodes **112** are also insulated from the SiC material **100** by a gate dielectric **116**. The field and gate dielectrics **114**, **116** may comprise the same or different materials. For example, the field dielectric **114** may be a thicker oxide and the gate dielectric **116** may be a thinner oxide.

A channel region **118** of a second conductivity type is formed in the SiC mesas **108** adjacent the opposing sidewalls **104** of each gate trench **102**. A source region **120** of the first conductivity type is formed above the channel region **118** in the SiC mesas **108** and adjacent the opposing sidewalls **104** of each gate trench **102**. In the case of an n-channel power MOSFET, the channel regions **118** have p-type conductivity and the source regions **120** have n-type conductivity. In the case of a p-channel power MOSFET, the channel regions **118** have n-type conductivity and the source regions **120** have p-type conductivity.

A channel contact region (out-of-view) of the second conductivity type may be formed above each channel region **118** in a different part of the SiC mesas **108** than the corresponding source region **120**. The channel contact regions are doped more heavily than the channel regions **118**, and provide an ohmic connection between an overlying source metal layer **122** and the channel regions **118**. Only the outline of the source metal layer **122** is shown in FIG. 1, so as to not obstruct other regions of the device below the source metal layer **122**. The source regions **120** are in ohmic connection with the source metal layer **122**. Conductive contacts **124** extending between the overlying source metal layer **122** and the channel contact regions and the source regions **120** complete the respective ohmic connections. Signals applied to the gate electrodes **112** control the conductive state of the channel regions **118**, thereby controlling current flow between the source regions **120** and an underlying current distribution layer **126** formed in the SiC material **100**. A drift region **128** is formed in the SiC material **100** below the current distribution layer **126**. A drain/collector region of the semiconductor device is below the drift region **128** and not shown for ease of illustration.

The semiconductor device also includes a shielding region **130** of the second conductivity type at the bottom **106** of a first subset of the gate trenches **102**. Each shielding region **130** is electrically connected to the corresponding buried electrode **110** in the lower part of the first subset of gate trenches **102** through an opening **132** in the insulating material **114** at the bottom **106** of the first subset of gate trenches **102**. For example, the shielding regions **130** may be in direct contact with the buried electrodes **110** at the bottom **106** of the first subset of gate trenches **102**. In other cases, a metal or other type of electrically conductive material may be provided between the buried electrodes **110** and the respective shielding regions **130**. In each case, the shielding regions **130** are at the same potential as the buried electrodes **110**. The buried electrodes **110** and the shielding regions **130**

may be electrically connected to the source metal layer **122** through conductive contacts **124** which extend from the source metal layer **122** to the buried electrodes **110** through an interlayer dielectric **136**, e.g., as shown in FIG. 3. The interlayer dielectric **136** is not shown in FIG. 1, so as to not obstruct other regions of the device below the interlayer dielectric **136**. The buried electrodes **110** and the shielding regions **130** included in the semiconductor device may instead be electrically connected to a potential other than source potential.

When turning off the semiconductor device via appropriate control of the signal applied to the gate electrodes **112**, the shielding regions **130** are at source (or other) potential suitable to build-up and a positive voltage in the SiC material **100**. The shielding regions **130** and the SiC material **100** are of the opposite conductivity type, and a blocking voltage builds up between these oppositely doped regions. The shielding regions **130** deplete all or most of the oppositely-doped SiC material **100** near the bottom **106** of the gate trenches **102**, protecting the gate dielectric **116** from excessive electric fields at the interfaces between the gate trenches **102** and the SiC material **100**. That is, the shielding regions **130** take up most of the electric field that builds up in the oppositely-doped SiC material **100** during blocking operation of the semiconductor device. In wideband semiconductor devices such as SiC devices, the electric field that builds up in the wideband semiconductor material **100** is approximately at the same level as the maximum allowed electric field for the gate dielectric **116**. The shielding regions **130** provided at the bottom **106** of the first subset of gate trenches **102** protect against overstressing of the gate dielectric **116**, ensuring reliable operation.

The shielding regions **130** may be arranged at corners of a grid and/or the shielding regions **130** may form part of a grid. For example, the shielding regions **130** and the gate trenches **102** may be arranged in a grid, or the shielding regions **130** alone may be arranged in a grid. The shielding regions **130** may have the same or different pitch than the gate trenches **102** where the pitch of the gate trenches **102** (or shielding regions **130**) may be a center-to-center distance of neighboring trenches **102** (or neighboring shielding regions **130**). Meshes of the grid may be rectangular or may have the shape of a rhombus.

The shielding regions **130** may be provided at the bottom of every second gate trench **102**, every third gate trench **102**, etc. The layout of the shielding regions **130** may be formed independent from the gate trench pitch, e.g., by providing a mask layer for the shielding region implant in the region of the trench structure. A deep implantation process is performed with the mask layer. In one embodiment, a multi-layer epitaxy process is used. For example, a first epitaxial layer may be formed, followed by the shielding region implant (e.g. p-type dopant species in the case of an n-channel device, or n-type dopant species in the case of a p-channel device), followed by formation of another epitaxial layer to avoid dopant tailing at the front side of the semiconductor device. Dopant tailing towards the front side of the device may effect device performance, e.g., by inhibiting the inversion channel which in turn reduces channel width. In another embodiment, the complete epitaxial structure is formed and then the shielding region implant is performed. The dopant species used to form the shielding regions **130** may be implanted into the SiC material **100** through the bottom **106** of the gate trenches **102**. In this case, the insulating material **114** at the bottom of every second, third, etc. gate trench **102** may be opened for the shielding region implant followed by the formation of contacts



between the buried electrode **110** or other material at the bottom **104** of the gate trenches **102** and the implanted shielding regions **130**. In another embodiment, the dopant species used to form the shielding regions **130** may be implanted into the SiC material **100** before the gate trenches **102** are formed. Typical p-type dopant species for SiC include beryllium, boron, aluminum, and gallium. Typical n-type dopant species for SiC include nitrogen and phosphorus. Other types of dopant species may be used to form the shielding regions **130**.

The shielding regions **130** may be varied in the lengthwise direction of the gate trenches **102** as shown in FIG. **4**. FIG. **4** is a cross-sectional view of the semiconductor device along the line labelled C-C' in FIG. **1**, which is along the lengthwise direction of one gate trench **102**. According to this embodiment, the shielding regions **130** extend in parallel with one another in lines that run parallel to the gate trenches **102**. Insulating material **114** is present at the bottom **106** of the gate trenches **102** between adjacent ones of the shielding regions **130** according to this embodiment, effectively isolating the shielding regions **130** from one another by the insulating material **114** which remains in the bottom **106** of the gate trenches **102**.

FIG. **5** illustrates an embodiment of a layout for the shielding regions **130** in which the shielding regions **130** are arranged in rows **200** which run in a direction (x) transverse to the lengthwise extension (y) of the gate trenches **102**. Two rows **200** of shielding regions **130** are shown in FIG. **5** for ease of illustration only. The semiconductor device may include any desired number of rows **200** of shielding regions **130**. The arrangement of shielding regions **130** is independent from the gate trench pitch, avoiding misalignment issues between the shielding regions **130** and the gate trenches **102**. In one embodiment, the direction (x) in which the rows **200** of shielding regions **130** run is orthogonal or nearly orthogonal to the lengthwise extension (y) of the gate trenches **102**. The term "nearly orthogonal" as used herein means that the rows **200** of shielding regions **130** may not run precisely orthogonal to the lengthwise extension (y) of the gate trenches **102**, e.g., due to process tolerance.

The shielding regions **130** may be contiguous over the length of the gate trenches **102**, as shown in FIG. **5**. Alternatively, at least some of the shielding regions **130** may be segmented over the length of the corresponding gate trenches **102**. In the case of segmented shielding regions **130**, the insulating material **114** may be present at the bottom **106** of the gate trenches **102** between adjacent rows **200** of the shielding regions **130**, e.g., as shown in FIG. **3**. In either case, the dopant species used to form the shielding regions **130** is implanted into the SiC material **100** before the gate trenches **102** are formed in the embodiment illustrated in FIG. **5**.

FIG. **6** illustrates another embodiment of a layout for the shielding regions **130** in which the shielding regions **130** are arranged in rows **300** which run in a direction (z) transverse to the lengthwise extension (y) of the gate trenches **102**. Two rows **300** of shielding regions **130** are shown in FIG. **6** for ease of illustration only. The semiconductor device may include any desired number of rows **300** of shielding regions **130**. The embodiment shown in FIG. **6** is similar to the embodiment shown in FIG. **5**. Different, however, the rows **300** of shielding regions **130** run in a direction (z) transverse but not orthogonal or nearly orthogonal to the lengthwise extension (y) of the gate trenches **102**. The transverse angle (a) between the rows **300** of shielding regions **130** and the gate trenches **102** may be determined by the implantation mask used to form the shielding regions **130**. Like the

embodiment in FIG. **5**, the dopant species used to form the rows **300** of shielding regions **130** illustrated in FIG. **6** is implanted into the SiC material **100** before the gate trenches **102** are formed.

FIG. **7** illustrates a partial cross-sectional view of another embodiment of a semiconductor device which has a shielding region **130** of the second conductivity type formed at the bottom **106** of a first subset of gate trenches **102**. The embodiment shown in FIG. **7** is similar to the embodiment shown in FIGS. **1-4**, and is taken along the same cross-sectional line A-A' as shown in FIG. **2**. Different, however, the semiconductor device also includes a non-linear junction **400** formed with the SiC material **100** at the bottom **106** of a second subset of the gate trenches **102** different than the first subset. The non-linear junctions **400** have an asymmetric response to an electric field, as opposed to an ohmic junction which has a symmetric response.

The non-linear junctions **400** may be formed by removing the insulating material **114** from the bottom **106** of the second subset of gate trenches **102** and then depositing the buried electrode material or a metal in the trench bottom **106** which contacts the exposed SiC material **100**. The shielding regions **130** and the non-linear junctions **400** may be arranged in an alternating manner below the gate trenches **102**.

According to the embodiment shown in FIG. **7**, a metal **402** such as Ti, TiN, Ti/TiN, Mo, MoN, WN, etc. is formed below the buried electrode **110** at the bottom **106** of the second subset of gate trenches **102**, the non-linear junction **400** is a Schottky junction, and the Schottky junction **400** is formed between the SiC material **100** and the metal **402** at the bottom **106** of the second subset of gate trenches **102**. The buried electrodes **110** formed in the lower part of the gate trenches **102** may comprise doped polysilicon or metal, as previously described herein. The same or different metal **402** may be formed below the buried electrodes **110** in the first subset of gate trenches **102** so that the shielding regions **130** contact the metal **402** at the bottom **106** of the first subset of gate trenches **102**.

The gate electrodes **112** may be formed in the gate trenches **102** with the underlying non-linear junctions **400** by recessing the electrically conductive material used to form the buried electrodes **110** such as doped polysilicon or metal, forming an intermediate oxide over the recessed buried electrode material, forming the gate dielectric **114** on the trench sidewalls **104**, and then forming the gate electrode **112** above the buried electrode **110**. The non-linear junctions **400** overcome the bipolar mode/action of SiC in normal operation, effectively integrating a unipolar Schottky diode into the semiconductor device. Alignment issues are also avoided, since the non-linear junctions **400** are formed at the gate trench bottom **106**.

FIG. **8** illustrates a partial cross-sectional view of another embodiment of a semiconductor device which has shielding regions **130** of the second conductivity type and non-linear junctions **400** formed in SiC material **100**. The embodiment shown in FIG. **8** is similar to the embodiment shown in FIG. **7**. Different, however, the shielding regions **130** formed at the bottom **106** of the first subset of gate trenches **102** contacts the corresponding buried electrode **110**. According to this embodiment, no metal is provided between the buried electrodes in the first subset of gate trenches and the underlying shielding regions.

FIG. **9** illustrates a partial cross-sectional view of another embodiment of a semiconductor device which has shielding regions **130** of the second conductivity type and non-linear junctions **400** formed in SiC material **100**. The embodiment



shown in FIG. 9 is similar to the embodiment shown in FIG. 8. Different, however, the non-linear junctions 400 are formed between the SiC material 100 and the corresponding buried electrode 110 at the bottom 106 of the second subset of gate trenches 102. According to this embodiment, no metal is provided between the buried electrodes 110 in the first subset of gate trenches 102 and the underlying shielding regions 130, and no metal is provided between the buried electrodes 110 in the second subset of gate trenches 102 and the underlying non-linear junctions 400. In one embodiment, the buried electrode material is p+ polysilicon which forms a Schottky junction with n-doped SiC. For gate trenches 102 without underlying shielding regions 130, good ohmic contact between the buried electrodes 110 (e.g. doped polysilicon or metal) and p-type SiC is desired. A pn diode or a Schottky diode is formed within the SiC material 100 between the shielding regions 130 and the oppositely-doped drift region 128.

FIGS. 10 and 11 illustrate respective partial cross-sectional views of additional embodiments of a semiconductor device which has shielding regions 130 of the second conductivity type and non-linear junctions 400 formed in SiC material 100. The embodiments shown in FIGS. 10 and 11 are similar to the embodiment shown in FIGS. 1-4, and are taken along the same cross-sectional line C-C' as in FIG. 4. In FIG. 10, a metal 402 is formed below the buried electrode 110 at the bottom 106 of the second subset of gate trenches 102. According to this embodiment, the non-linear junctions 400 are Schottky junctions formed between the SiC material 100 and the metal 402 at the bottom 106 of the second subset of gate trenches 102. The non-linear junctions 400 may be formed by removing the insulating material 114 from the bottom 106 of the second subset of gate trenches 102 and depositing the metal 402 in the trench bottom 106 before depositing the buried electrode material. In FIG. 11, the metal is omitted from the bottom 106 of the second subset of gate trenches 102. According to this embodiment, the non-linear junctions 400 are formed between the SiC material 100 and the corresponding buried electrode 110 in the lower part of the second subset of gate trenches 102. The non-linear junctions 400 may be formed by depositing the buried electrode material in the lower part of the second subset of gate trenches 102 without first depositing a metal on the trench bottom 106, so that the buried electrodes 110 in the second subset of gate trenches 102 are in contact with the exposed SiC material 100.

FIGS. 12 through 14 illustrate respective partial top-down plan views of different embodiments of the shielding region layout in conjunction with the non-linear junction layout. The layouts are shown with respect to the gate trenches 102, but the contents of the gate trenches 102 are not shown so that the shielding regions 130 and non-linear junctions 400 are visible.

In FIG. 12, the shielding regions 130 are segmented and extend in parallel with one another in lines that run parallel to the gate trenches 102 and to the non-linear junctions 400 formed with the SiC material 100 at the bottom 106 of the gate trenches 102. In FIG. 13, some of the shielding regions 130 are segmented and other ones of the shielding regions 130 are contiguous over the length of the gate trenches 102. The non-linear junction 400 formed below the contiguous shielding region 130 is out of view in FIG. 13. In FIG. 14, the segmented shielding regions 130 are arranged in a checkerboard-like pattern. In each embodiment illustrated in FIGS. 12 through 14, the shielding region layout may be formed by providing a mask layer for the shielding region implant in the region of the trench structure. A deep implan-

tation process is performed with the mask layer. A multi-layer or single-layer epitaxy process may be used to form the SiC material 100 in which the shielding regions 130 are formed, as previously described herein.

FIG. 15 illustrates a partial top-down plan view of another embodiment of the shielding region layout in conjunction with the non-linear junction layout. According to this embodiment, an insulating material 114 is present at the bottom 106 of the gate trenches 102 between adjacent rows 500 of the shielding regions 130 to divide the non-linear junction 400 in the same gate trench 102 into a plurality of non-linear junction segments 502 separated from one another by the insulating material 114. The non-linear junction segments 502 may be formed by forming openings in the insulating material 114 at the bottom 106 of the gate trenches 102 and depositing a metal at the trench bottom 106 before depositing the buried electrode material, or just depositing the buried electrode material in the lower part of the gate trenches 102. The shielding regions 130 formed in the SiC material 100 below the gate trenches 102 may be formed in stripes along a direction (x) transverse to the lengthwise extension (y) of the gate trenches 102 as shown in FIG. 15, or instead may be segmented along the transverse direction (x). The transverse direction (x) may or may not be orthogonal to the lengthwise extension (y) of the gate trenches 102, as previously explained herein.

In some embodiments, the shielding regions 130 are arranged only at the bottom of a first subset of gate trenches 102 and the non-linear junctions 400 are arranged only at the bottom of a second subset of gate trenches 102. In this case, the shielding regions 130 and the non-linear junctions 400 may alternate along a direction transverse (e.g. with an angle of at least 40° and at most 140°) to the sidewalls of the gate trenches 102 (e.g., transverse to the lengthwise extension in case of stripe-shaped trenches). In other embodiments, at least one of the shielding regions 130 and the non-linear junctions 400 may be arranged at the bottom of the first subset of gate trenches 102 and at the bottom of the second subset of gate trenches 102. In this case, the shielding regions 130 and the non-linear junctions 400 may alternate at least along a direction parallel to the bottom of the gate trenches 102 (e.g., along the lengthwise extension in case of stripe-shaped trenches). In addition, the shielding regions 130 and the non-linear junctions 400 may also alternate along one of the gate trenches 102, in particular along the lengthwise extension.

Terms such as “first”, “second”, and the like, are used to describe various elements, regions, sections, etc. and are also not intended to be limiting. Like terms refer to like elements throughout the description.

As used herein, the terms “having”, “containing”, “including”, “comprising” and the like are open ended terms that indicate the presence of stated elements or features, but do not preclude additional elements or features. The articles “a”, “an” and “the” are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

It is to be understood that the features of the various embodiments described herein may be combined with each other, unless specifically noted otherwise.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present invention. This application is intended to cover any adaptations or variations of the specific



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embodiments discussed herein. Therefore, it is intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. A semiconductor device, comprising:  
a SiC material of a first conductivity type;  
a plurality of trenches extending into the SiC material, each trench having opposing sidewalls and a bottom;  
a first electrode formed in a lower part of the trenches;  
a second electrode formed in an upper part of the trenches and insulated from both the first electrode and the SiC material;  
a channel region of a second conductivity type adjacent the opposing sidewalls of each trench;  
a source region of the first conductivity type above the channel region and adjacent the opposing sidewalls of each trench;  
a shielding region of the second conductivity type at the bottom of a first subset of the trenches, each shielding region being electrically connected to the corresponding first electrode through an opening in an insulating material at the bottom of the first subset of trenches; and  
a non-linear junction formed with the SiC material at the bottom of a second subset of the trenches different than the first subset.
2. The semiconductor device of claim 1, wherein the non-linear junction is formed between the SiC material and the first electrode at the bottom of the second subset of the trenches.
3. The semiconductor device of claim 2, wherein the first electrode formed in the lower part of the trenches comprises doped polysilicon.
4. The semiconductor device of claim 1, wherein a metal is formed below the first electrode in the second subset of trenches, wherein the non-linear junction is a Schottky junction, and wherein the Schottky junction is formed between the SiC material and the metal at the bottom of the second subset of the trenches.
5. The semiconductor device of claim 4, wherein the first electrode formed in the lower part of the trenches comprises a semiconductor material.
6. The semiconductor device of claim 4, wherein the first electrode contacts the shielding region at the bottom of the first subset of trenches.
7. The semiconductor device of claim 4, wherein a metal is formed below the first electrode in the first subset of the trenches, and wherein the metal contacts the shielding region at the bottom of the first subset of the trenches.
8. The semiconductor device of claim 1, wherein the shielding regions and the non-linear junctions are arranged in an alternating manner below successive ones of the trenches.
9. The semiconductor device of claim 1, wherein the shielding regions are arranged at corners of a grid or wherein the shielding regions form part of a grid.
10. The semiconductor device of claim 9, wherein the insulating material is present at the bottom of the trenches between adjacent ones of the shielding regions.

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11. The semiconductor device of claim 1, wherein the shielding regions extend in parallel with one another in lines that run parallel to the trenches, and wherein the shielding regions have a different pitch than the trenches.

12. The semiconductor device of claim 1, wherein the shielding regions are arranged at the bottom of the first subset of trenches and at the bottom of the second subset of trenches, and wherein some of the shielding regions are segmented and other ones of the shielding regions are contiguous over a length of the trenches.

13. The semiconductor device of claim 1, wherein the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of the trenches.

14. A semiconductor device, comprising:  
a SiC material of a first conductivity type;  
a plurality of trenches extending into the SiC material, each trench having opposing sidewalls and a bottom;  
a first electrode formed in a lower part of the trenches;  
a second electrode formed in an upper part of the trenches and insulated from both the first electrode and the SiC material;  
a channel region of a second conductivity type adjacent the opposing sidewalls of each trench;  
a source region of the first conductivity type above the channel region and adjacent the opposing sidewalls of each trench; and  
a shielding region of the second conductivity type at the bottom of the trenches and electrically connected to the corresponding first electrode through an opening in an insulating material at the bottom of the trenches, wherein the shielding regions are arranged in rows which run in a direction transverse to a lengthwise extension of the trenches.

15. The semiconductor device of claim 14, wherein the insulating material is present at the bottom of the trenches between adjacent rows of the shielding regions.

16. The semiconductor device of claim 14, further comprising a non-linear junction formed with the SiC material at the bottom of the trenches.

17. The semiconductor device of claim 16, wherein a metal is formed below the first electrode in the trenches, wherein the non-linear junction is a Schottky junction, and wherein the Schottky junction is formed between the SiC material and the metal at the bottom of the trenches.

18. The semiconductor device of claim 16, wherein the insulating material is present at the bottom of the trenches between adjacent rows of the shielding regions to divide the non-linear junction in the same trench into a plurality of non-linear junction segments separated from one another by the insulating material.

19. The semiconductor device of claim 14, wherein the shielding regions are contiguous over a length of the trenches.

20. The semiconductor device of claim 14, wherein the rows of shielding regions run in a direction orthogonal or nearly orthogonal to the lengthwise extension of the trenches.

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